

Breakthrough Air Force Capabilities Spawned By Basic Research

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Introduction

For over fifty years, the Air Force Research Laboratory's (AFRL) Air Force Office of Scientific Research (AFOSR) has produced major scientific discoveries that have led to the creation and development of revolutionary capabilities for the Air Force. These scientific discoveries have laid the ground work for the technological innovation that has created the superior air and space force that is the modern United States Air Force. A continued robust investment in basic research will lead to capabilities that have the potential to reshape Air Force thinking, doctrine and operations in the future.

Two key Air Force strategy documents, "The U.S. Air Force Transformation Flight Plan 2004" and "The U.S. Air Force Posture Statement 2006," have pointed out the importance of a robust science and technology (S&T) investment in achieving the future capabilities needed to meet a wide range of conventional and asymmetric threats.¹ The 2006 Posture Statement adds the critical area of cyberspace to the more established Air Force mission domains of air and space by articulating a mission statement that reads "The mission of the U.S. Air Force is to deliver sovereign options for the defense of the United States of America and its global interests—to fly and fight in air, space and cyberspace."² This strategy has embraced a new technology vision to guide the Air Force S&T program—"Anticipate, Find, Fix, Track, Target, Engage, Assess... Anything, Anytime, Anywhere."³

In response to the new strategic guidance from Air Force leadership, the Air Force Research Laboratory, as part of its Integrated Capability-Based Planning Process, has developed eight Focused Long Term Challenges (FLTCs).⁴ The FLTCs will guide the S&T program in developing new technology solutions required to provide the future capabilities needed by the Air Force and the joint warfighter, as articulated in the 2006 Quadrennial Defense Review (QDR).⁵ The eight FLTCs are:

FLTC 1: Anticipatory Command, Control and Intelligence (C2I). Anticipate enemy actions and respond with synchronized management of battlespace effects.

FLTC 2: Unprecedented Proactive Surveillance and Reconnaissance (S&R). Proactively find, fix, and track anything, anytime, anywhere with agile and immediate C4ISR.

¹ U.S. Air Force, "The U.S. Air Force Transformation Flight Plan 2004." Available online at <http://www.oft.osd.mil/library/library_files/document_385_2004_USAF_Transformation_Flight_Plan.pdf>.

² U.S. Air Force, "The U.S. Air Force Posture Statement 2006." Available online at <<http://www.af.mil/shared/media/document/AFD-060302-001.pdf>>.

³ Ibid.

⁴ Air Force Research Laboratory, "Focused Long Term Challenges (FLTCs): Integrated Capability Planning Process Status Update," April 21, 2006. Available online at <http://www.afrl.af.mil/FLTC_Briefing.pdf>.

⁵ "Quadrennial Defense Review Report 2006," February 6, 2006. Available online at <<http://www.defenselink.mil/qdr/report/Report20060203.pdf>>.

FLTC 3: Dominant Difficult Surface Target Engagement/Defeat. Detect, tag, track, identify, and target adversaries, improvised explosive devices (IEDs), and chemical, biological, radiological, nuclear, and explosive (CBRNE) threats in congested or concealed areas and create desired effects.

FLTC4: Persistent and Responsive Precision Engagement. Maneuver through anti-access or area denied environments to deliver effects rapidly and/or persistently.

FLTC 5: Assured Operations in High Threat Environments. Achieve mission objectives with impunity against full spectrum threats, from anti-access Integrated Air Defense Systems (IADS) to cyber.

FLTC 6: Dominant Offensive Cyber Engagement. Conduct full spectrum cyber/information operations against military forces, leadership, and infrastructure.

FLTC 7: On-Demand Theater Force Projection, Anywhere. Responsive deployment of flexible ground, information, and space capabilities for the theater commander.

FLTC 8: Affordable Mission Generation and Sustainment. Affordably maximize mission capability, readiness, reliability and maintainability of current and future fleets.

The AFOSR is developing Discovery Challenge Thrusts (DCTs) that will focus the basic research program to address the Air Force FLTCs. The DCTs will be high-impact, multidisciplinary, basic research initiatives that typically will support multiple FLTCs. The DCTs will not be discussed further here, as they are a work in progress as of this writing. Instead, this paper will focus on those scientific discoveries that have already lead to new capabilities for the Air Force, as well as those discoveries that will lead to the new capabilities envisioned in the 2004 Flight Plan and 2006 Posture Statement and those yet to be envisioned. New scientific research being supported by AFOSR will undoubtedly lead to novel options for yet undreamed of new capabilities for war fighting, peace keeping, humanitarian, and stabilization and reconstruction missions for the Air Force and the Department of Defense.

The Air Force Office of Scientific Research and Breakthrough Technologies Since 1950

Since its establishment in the early 1950s, AFOSR has funded a wide variety of basic research that has had far-reaching implications in not only defense, but also commercial and civilian applications. The following three examples per decade are only a few of the numerous revolutionary technologies developed by Air Force scientists and researchers.

1950s

- *MASER/LASER*. In the early 1950s, AFOSR-funded research led to the development of the MASER (Microwave Amplification by Stimulated Emission of Radiation) by Dr. Charles Townes. Further research by Dr. Townes and a colleague, Dr. Arthur Schawlow, led to work on the principles of the LASER (Light Amplification by Stimulated Emission of Radiation). For his work on the maser and laser, Dr. Townes shared the Nobel Prize in physics in 1964.⁶
- *Kalman Filter*. Under AFOSR support in the 1950s, Dr. Rudolph Kalman developed a technique of combining and filtering information from multiple sensor sources that became known as the Kalman Filter. The Kalman Filter eventually became a key component of flight control and guidance technology.
- *Integrated Circuits*. AFOSR was a pioneer in the theoretical and application work associated with the integrated circuit (IC) with Dr. Jack Kilby, through AFOSR funding, demonstrating the first functional integrated circuit in 1958.⁷

1960s

- *Computer Mouse*. A 1960 grant to Dr. Douglas Engelbart for research on augmenting human intellect and the potential for computers to assist in complex decisionmaking processes ultimately led to the first computer mouse prototype.⁸
- *Global Positioning System*. A 1967 AFOSR grant assisted Dr. Byron Knowles from Texas A&M University in developing a design for a low-cost Global Positioning System (GPS).⁹
- *Flight Pressure Suit and Anti-Gravity Valve*. AFOSR-supported research in the 1960s on cardiovascular blood dynamics under G force stress led to the development of

⁶ Air Force Office of Scientific Research, "AFOSR at 50: Five Decades of Research that Helped Change the World," *Research Highlights*, Mar/Apr 2002, 1. Available online at http://www.afosr.af.mil/Documents/ResearchHighlights/pub_2002MarApr.pdf.

⁷ Air Force Office of Scientific Research, "AFOSR Decade Highlights." Available online at http://www.afosr.af.mil/AboutAFOSR/about_history.htm.

⁸ Air Force Office of Scientific Research, "AFOSR at 50: Five Decades of Research that Helped Change the World," *Research Highlights*, Mar/Apr 2002, 1. Available online at http://www.afosr.af.mil/Documents/ResearchHighlights/pub_2002MarApr.pdf.

⁹ Air Force Office of Scientific Research, "AFOSR Decade Highlights." Available online at http://www.afosr.af.mil/AboutAFOSR/about_history.htm.

anti-gravity technology that allowed pilots to withstand the high G forces involved in high performance aircraft maneuvering.¹⁰

1970s

- *Superplastic Forming Production Techniques*. In the 1970s, AFOSR sponsored research on ways to increase the strength and fatigue resistance of titanium, aluminum, and nickel alloys used for airframes. This research led to the development of superplastic forming production techniques that eventually reduced the production costs and weight of numerous airplane components.¹¹
- *Superconductivity*. From 1968–1975, AFOSR supported research on superconductivity by Dr. Brian Josephson. Dr. Josephson received the Nobel Prize in physics in 1973 for developing the world’s most sensitive magnetometers and fastest, lowest power, switching elements, leading to a new generation of computers.¹²
- *Chemical Oxygen-Iodine Laser (COIL)*. COIL is the world’s shortest wavelength, high-powered, chemical laser, operates on an atomic iodine laser transition, and emits light with a wavelength of 1.315 micrometers.¹³ COIL was invented and patented in late 1977 by three Air Force officers and a civilian scientist working out of the Air Force Weapons Laboratory.

1980s

- *Environmental Processing Techniques*. In the early 1980s, AFOSR research looked at the development of techniques and processes to treat wastes from Air Force related programs. The research led to, among other technologies, the development of a new strain of bacteria that could degrade high-concentrations of creosol.¹⁴
- *High-Efficiency Swept Shock Compressor Blades*. AFOSR-sponsored research looked at making rotor blades in axial flow compressors more efficient. This research led to improved compressor efficiency by an astounding 90 percent and reduced fuel consumption.¹⁵
- *Low-Temperature Gallium Arsenide*. Low-temperature gallium arsenide, a semiconducting material used in the fabrication of microelectric devices, was discovered in 1985 under an AFOSR-funded program. It quickly transitioned to industry and was used in MILSTAR satellites, as well as the B-2 bomber, F-15, F-16, F-18 and F-22 fighters.¹⁶

¹⁰ Ibid.

¹¹ Ibid.

¹² Air Force Office of Scientific Research, “AFOSR at 50: Five Decades of Research that Helped Change the World,” *Research Highlights*, Mar/Apr 2002, 1. Available online at <http://www.afosr.af.mil/Documents/ResearchHighlights/pub_2002MarApr.pdf>.

¹³ United States Air Force, “Chemical Oxygen-Iodine Laser (COIL),” July 2002. Available online at <<http://www.de.af.mil/Factsheets/COIL.pdf>>.

¹⁴ Air Force Office of Scientific Research, “AFOSR Decade Highlights.” Available online at <http://www.afosr.af.mil/AboutAFOSR/about_history.htm>.

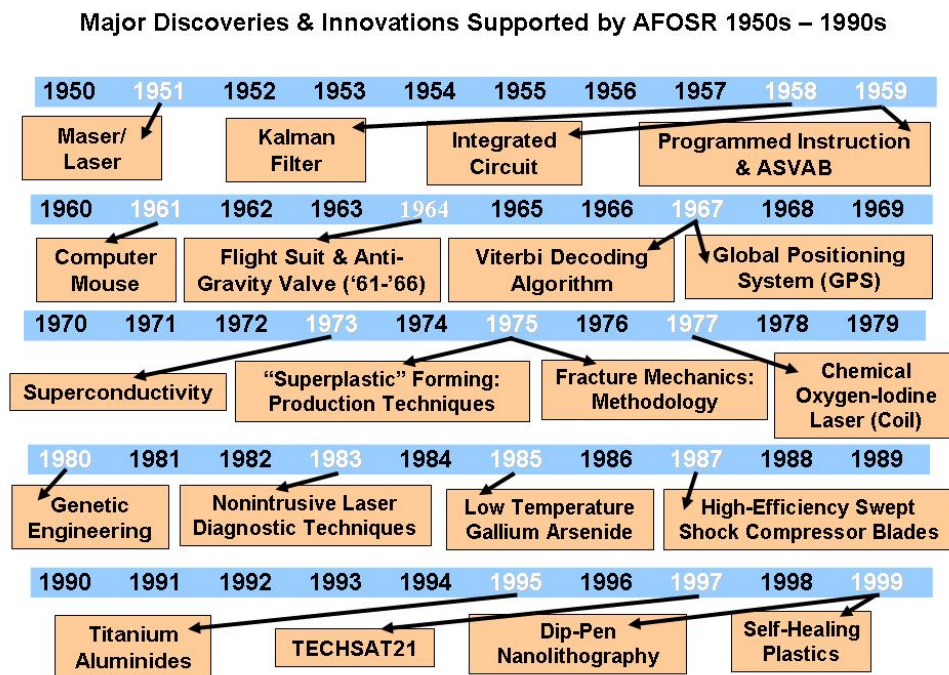
¹⁵ Ibid.

¹⁶ Ibid.

1990s

- *Titanium Aluminides*. AFOSR-sponsored research looked at titanium aluminides, which are known for their lightness, high-strength, and high-temperature oxidation stability. AFOSR researchers conducted research leading to their application in aircraft engine components.¹⁷
- *Dip Pen Nanolithography*. Developed in the 1990's with AFOSR support, dip pen nanolithography is used to manipulate nanoparticles with application to novel materials and biotechnology.¹⁸
- *Technology Satellite for the 21st Century (TechSat21)*. In the late 1990s, AFOSR funded a number of projects in the areas of sparse aperture radar, collective behavior, micro-propulsion, and ionospheric science. Basic research in these areas contributed to the TechSat21 program, a space program whose objective was to create microsattellites about one-tenth the size of then-current conventional satellites.¹⁹

Figure 1: AFOSR Breakthrough Research²⁰



¹⁷ Ibid.

¹⁸ Piner, R.D., Zhu, J., Xu, F., Hong, S., and Mirkin, C.A., "Dip-Pen Nanolithography," *Science*, Vol. 283, January 1999, 661-663.

¹⁹ Air Force Office of Scientific Research, "AFOSR Decade Highlights." Available online at <http://www.afosr.af.mil/AboutAFOSR/about_history.htm>.

²⁰ Lee, E.J., Air Force Office of Scientific Research, "20th Annual Briefing for Industry," August 15, 2006. Power Point Presentation.

As this brief history demonstrates, AFOSR investment in basic research since the 1950s has laid the foundation for numerous cutting edge technologies that have revolutionized the Nation's Air Force. Two examples of technologies developed from AFOSR sponsored research that continue to have applicability to the modern Air Force, years after their first development, are the Kalman Filter and the Airborne Laser. These examples demonstrate how separate scientific advances combine to provide outstanding new capabilities and most often are the foundation for applications in many different areas.

Kalman Filter

In the late 1950s and early 1960s, AFOSR focused much of its research effort on issues relating to supersonic flight and aircraft guidance and flight control mechanisms. AFOSR awarded numerous contracts on research in nonlinear systems and the use of modern mathematical statistical methods in estimation. In 1958, one such contract was awarded to the Research Institute for Advanced Studies (RIAS) for the development and application of statistical filtering theory. The principal researcher at RIAS on this contract was a mathematician named Dr. Rudolph Kalman.²¹

Dr. Kalman quickly began research on the topic, publishing a seminal paper in 1960 describing a recursive solution to the data linear filtering problem entitled "A New Approach to Linear Filtering and Prediction Problems." In 1960, a second researcher, Dr. Richard Bucy, joined Kalman's team. The two specialists wrote a series of papers that led to the development of a technique of combining and filtering information from multiple sensor sources that became known as the Kalman Filter.²² Essentially, the Kalman filter is "a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of a process, in a way that minimizes the mean of the squared error."²³

The Kalman Filter became a key component of flight control and guidance technology and was embraced by both the Air Force and the National Aeronautics and Space Administration (NASA), which used it in the Ranger and Mariner space missions and to guide the Apollo 11 lunar module to the moon's surface. The Kalman Filter also was used in other Air Force and military systems, including phased-array radars to track missiles, sonar ranging, missile autopilots, and rockets.²⁴

More than fifty years after it was first developed, the Kalman Filter is a component in nearly all modern, high-speed, military and commercial flight vehicles and has seen

²¹ Air Force Research Laboratory History Program, "Kalman Filter and Its Impact," *"Breakthrough" Technologies Developed by the Air Force Research Laboratory and its Predecessors* (Air Force Research Laboratory History Program, December 21, 2005), 167.

²² *Ibid.*, 168.

²³ Welch, G. and Bishop, G., "An Introduction to the Kalman Filter," July 24, 2006. Available online at <www.cs.unc.edu/~welch/kalman/kalmanIntro.html>.

²⁴ Air Force Research Laboratory History Program, "Kalman Filter and Its Impact," *"Breakthrough" Technologies Developed by the Air Force Research Laboratory and its Predecessors* (Air Force Research Laboratory History Program, December 21, 2005), 169.

widespread use in other civilian applications, including computer software programs, marine navigation, demographic and atmospheric modeling, and image processing. The Kalman Filter is an example of a breakthrough technology developed by AFOSR that has impacted technology for decades and undoubtedly has potential revolutionary applications for use in future military, space, and commercial developments.

Airborne Laser

The foundation for an airborne laser capability was laid by the breakthrough scientific discoveries in masers and lasers that began in the 1950s, as chronicled earlier in this section. Those early successes led the AFOSR, as early as the 1970s, to invest in fundamental scientific studies in chemistry and physics that led to the understanding necessary to develop the Chemical Oxygen Iodine Laser (COIL), which is a key enabling capability for the Air Force's Airborne Laser program of today.

From those early scientific beginnings, the Airborne Laser Laboratory (ALL) was established at Kirtland Air Force Base, New Mexico. The roots of the ALL can be traced back to 1962, when the Department of Defense's Advanced Research Projects Agency (ARPA) funded research at the Air Force Special Weapons Center (AFSWC) on the potential military use of lasers. In 1968, the Air Force Weapons Laboratory (AFWL), formerly the AFSWC and now the Directed Energy Directorate of AFRL, was authorized to begin a new program on building and testing a CO² gas dynamic laser. Shortly thereafter, research into the idea of mounting a laser on an airplane as an anti-missile system began.²⁵

After a series of initial developments and tests, the ALL program made significant advances in 1972, when technicians fired a ground-based laser against stationary targets. The next success occurred on November 13, 1973, when the laser was used against a Northrop MQM-33B, a 12-foot-long, radio-controlled, aerial drone in an attempt to knock it out of the air.²⁶ While the laser did hit the aerial drone, disabling it and causing it to crash, it only caused minor damage. Technicians conducted a second test the next day and shot down and destroyed the target, marking the first ever successful attempt to shoot down an aerial target by a ground based high-energy laser.

The next stages of the ALL revolved around three key cycles: demonstrating that an airborne pointing and tracking (APT) system could accurately track an aerial target; aligning a low-power beam with the APT and then directing the beam out of the turret on top of the aircraft to an aerial target; and combining a high-powered beam with the APT to shoot down the targets.²⁷ The three cycles were finally completed in 1983, and on May 16, 1983, the ALL, which consisted of a gas-dynamic laser mounted on a modified

²⁵ Ibid., 34.

²⁶ United States Air Force, "A Brief History of the Airborne Laser," February 27, 2003. Available online at <<http://www.de.afrl.af.mil/Factsheets/ABLHistory.swf>>.

²⁷ Air Force Research Laboratory History Program, "Airborne Laser Laboratory," *"Breakthrough" Technologies Developed by the Air Force Research Laboratory and its Predecessors* (Air Force Research Laboratory History Program, December 21, 2005), 36.

version of a KC-135, destroyed an AIM-9B sidewinder missile.²⁸ In subsequent tests in May and June 1983, the ALL destroyed four other AIM-9B missiles.

The final test for the ALL took place in September 1983. In a joint experiment with the Navy, the ALL shot down and destroyed three 23-foot-long, ground-launched, BMQ-34A Navy drones. The interception and destruction of the three drones signaled that the ALL program was a resounding success, proving that the goal of airborne anti-missile defense was indeed realistic. While the ALL was retired in 1984, it served as the technical bridge for the current Airborne Laser (ABL) program, which was initiated by the Air Force in 1996.



The Airborne Laser Laboratory Aircraft

Transferred to the Missile Defense Agency in 2001, the ABL program is an integral component of the Ballistic Missile Defense System. The ABL program places a megawatt-class, high-energy Chemical Oxygen Iodine Laser (COIL) on a modified Boeing 747-400F aircraft with the mission of

detecting, tracking, targeting, and destroying ballistic missiles during the boost-phase.²⁹

COIL is the world's shortest wavelength, high-powered chemical laser, operates on an atomic iodine laser transition, and emits light with a wavelength of 1.315 micrometers.³⁰ COIL was invented and patented in late 1977 by three Air Force officers and a civilian scientist working out of the Air Force Weapons Laboratory.³¹ AFOSR also contributed to the development of the ABL program through research that made major advances in our understanding and eventual development of adaptive optics and atmospheric compensation techniques. AFOSR support of these crucial research areas dates back over 27 years, at various universities and research centers, and through funding programs at AFRL's Directed Energy Directorate, led by Dr. Robert Fugate.³² In particular, AFOSR was involved with atmospheric characterization—understanding the atmosphere, including high altitude cloud ice crystal formation, moisture content, winds, etc., to optimize ABL performance. Ultimately, AFOSR contributions to the evolution and development of COIL and research on adaptive optics will be critical to the success of the ABL program. A flight test with the goal of destroying a ballistic missile is planned for late 2008.

²⁸ Ibid., 39.

²⁹ Boeing Integrated Defense Systems, "Airborne Laser Backgrounder," February 2006. Available online at <http://www.boeing.com/defense-space/military/abl/doc_src/ABL_overview.pdf>.

³⁰ United States Air Force, "Chemical Oxygen-Iodine Laser (COIL)," July 2002. Available online at <<http://www.de.af.mil/Factsheets/COIL.pdf>>.

³¹ Air Force Research Laboratory History Program, "Chemical Oxygen Iodine Laser," *"Breakthrough" Technologies Developed by the Air Force Research Laboratory and its Predecessors* (Air Force Research Laboratory History Program, December 21, 2005), 59.

³² Keller, J., "Adaptive Optics Blends the Best of Electronic and Optoelectronic Technologies," *Military & Aerospace Electronics*, July 2004.

Promise for the Future

Basic research by its very nature is generic in the sense that the results may provide new understanding that will have applications in many areas. Quite frequently, the area where a new scientific discovery is made is far from the actual field where that new understanding was anticipated to have its most likely application. Thus, an investment in basic research will often provide options that create new “undreamed of” capabilities as an added benefit to providing the foundation for new capabilities expected at the outset of the research. The unexpected result or application is what creates the excitement of the research enterprise and the promise of unanticipated new technical capabilities.

This section discusses some examples of current or recent AFOSR investments in basic research and a few of the expected new capabilities that likely will arise from those investments. The discussion focuses on research that will contribute in a significant way to meeting many of the challenges articulated in the eight Air Force FLTCs. These challenges relate directly to the three Air Force mission domains of air, space, and cyberspace.

Autonomous, Unmanned Operators

Unmanned aerial vehicles (UAVs) have been in use by the Air Force and other components of the national security community for several years. Along with UAVs, other types of autonomous or semi-autonomous agents, such as robots and unmanned ground vehicles (UGVs), have also played a role in such operations as surveillance, reconnaissance, and search and rescue for both military missions and civilian disaster relief. In the future, even combat operations may involve to a much larger extent the use of semi-autonomous, unmanned vehicles known as Unmanned Combat Air Systems (UCAS) to deliver munitions to a target.³³

A key technical issue with all autonomous systems is how to control them. Control of groups or swarms of unmanned vehicles, whether working cooperatively or individually, is a scientific challenge being investigated by the AFOSR and other national security research organizations.

The AFOSR research described below will provide significant new capabilities for autonomous operations for the Air Force and the national and homeland security communities. That research should lead to fully autonomous systems of heterogeneous vehicles that can work independently or cooperatively to conduct a wide range of missions depending on the scenarios encountered.

At present, most unmanned vehicles do not have the flexibility and range of performance characteristics that would allow for complete autonomy for an entire mission. The

³³ Barry, C. and Zimet, E., “UCAVs—Technological, Policy and Operational Challenges,” *Defense Horizons* 3, (Washington, DC: National Defense University Press, October 2001).

guidance and mission planning systems of most UAVs do not have the ability to recognize and react to unexpected changes in operating conditions. This problem is greatly compounded when additional agents are added to the scenario, as may be the case with swarms of UAVs.³⁴ In this case, each vehicle must resolve information regarding actions and impending activities of the other vehicles and be able to communicate effectively its actions with manned and other unmanned members of its team, as well as with other teams of vehicles and control centers providing ancillary support to the mission.



“Swarm” of UAVs & Other Flight Vehicles

Although AFOSR-supported university research focused on control of UAVs for a number of years, this research area really took off in 2001. That year, AFOSR initiated the support of a number of multi-university teams under the Multidisciplinary University Research Initiative (MURI) program. The first team was led by Dr. Jeff Shamma at the University of California at Los Angeles (UCLA) and included members from California Institute of Technology (Cal Tech), Massachusetts Institute of Technology (MIT), and Cornell University under a project titled “Cooperative Control of Distributed

Autonomous Vehicles in Adversarial Environments.” One of the key goals of the UCLA-led effort was to investigate issues in the deployment of large-scale networks of autonomous vehicles and to derive path-planning schemes for such complex collective behavior from simple individual behavior. A major accomplishment from this group was the development and testing of a linear programming-based algorithm that can be used for effective, multi-vehicle path planning in an adversarial environment.³⁵

In 2002, a second MURI team effort led by Dr. Geir Dullerud at the University of Illinois, with additional team members from MIT, Stanford University, UCLA, and the University of California at Santa Barbara (UCSB), began under AFOSR support. This project, titled “Cooperative Networked Control of Dynamic Peer-to-Peer Vehicle Systems,” is focused on development of the control algorithms and internal software needed to create systems that are verifiably robust. Dullerud’s team at Illinois has developed and refined a dynamic testbed for networked and decentralized control of UAVs using hovercraft to test and verify new control algorithms and refine operational scenarios and strategies for networked UAVs. Although a number of other autonomous, multivehicle testbeds are in use at other universities, the HoTDeC (Hovercraft Testbed for Networked and Decentralized Control) is a unique facility consisting of multiple autonomous hovercraft that are wirelessly networked and can be commanded from the

³⁴ Valenti, M., Bethke, B., Fiore, G., How, J.P., and Feron, E., “Indoor Multi-Vehicle flight Testbed for Fault Detection, Isolation and Recovery,” *Proceedings of the AIAA Guidance, Navigation and Control Conference*, August 2006.

³⁵ Chasparis, G.C., and Shamma, J.S., “Linear-Programming-Based Multi-Vehicle Path Planning with Adversaries,” *Proceedings of the American Control Conference*, June 2005.

internet. The ability to allow command from the internet allows for the support of control algorithms that have their decisionmaking and computing resources distributed around the internet.³⁶

A third MURI research team currently being supported by AFOSR began in 2003 and is led by Dr. Eric Johnson at Georgia Institute of Technology (Georgia Tech), with team members from MIT, UCLA and Virginia Polytechnic Institute and State University (Virginia Tech). A major focus of this research effort is the incorporation of active vision to replace or complement the more traditional types of sensors used in UAVs. Thus, this MURI project is titled “Active-Vision Control Systems for Complex Adversarial 3-D Environments.” Johnson’s team utilized 2-D and 3-D imagery from different sensors, such as radar, infra-red and visual, to enable UAVs to autonomously detect and engage targets in uncertain, complex, 3-D, adversarial environments.³⁷ Previous work by Dr. Allen Tannenbaum’s lab, as part of the Georgia Tech MURI team, has made significant progress in addressing solutions to two of the most critical problems in this area, visual tracking and object recognition.³⁸ This research has allowed for what is believed to be the first ever purely vision-based formation flight of UAVs, which was achieved by the Georgia Tech team in a test flight on June 15, 2006.³⁹ Vision-based formation flight is believed by many to be critical to allowing UAVs, particularly Micro Air Vehicles (MAVs), to operate effectively in urban environments.

One of the crucial issues with autonomous operators deals with the fusion of information from disparate sensors on robots and UAVs that are spatially and temporally separated and yet must act as a team, often with human command and control in the loop. A related issue is getting that disparate, raw, sensor data into a form of information useful for decisionmakers. This major issue is currently the main thrust of another AFOSR supported, multi-institution research project known as an AFOSR Partnership for Research Excellence and Transition (PRET).⁴⁰ This project, titled “Information Fusion for Command and Control: The Translation of Raw Data to Actionable Knowledge and Decision,” is led by Dr. Katia Sycara at the Robotics Institute at Carnegie Mellon University (CMU), with partners from the University of Pittsburgh, Northrup Grumman, and the Munitions and Information Directorates of the Air Force Research Laboratory.⁴¹

³⁶ Stubbs, A., Vladimerou, A., Fulford, A.T., King, D., Strick, J., and Dullerud, G.E., “Multivehicle Systems Control over Networks,” *IEEE Control Systems Magazine*, June 2006, 56-69.

³⁷ Johnson, E.N., Calise, A.J., Tannenbaum, A.R., Soatto, S., Hovakimyan, N., and Yezzi, A.J., “Active-Vision Control Systems for Complex Adversarial 3-D Environments,” *Proceedings of the American Control Conference*, June 2005.

³⁸ Tannenbaum, A. Yezzi, A., and Goldstein, A., “Visual Tracking and Object Recognition,” *Proceedings of the 5th International Federation of Automatic Control*, July 2001.

³⁹ AVCS MURI Program 3rd Annual Review, November 2006. Available online at <<http://www.controls.ae.gatech.edu/avcs>>.

⁴⁰ AFOSR Partnerships for Research Excellence and Transition (PRET). Available online at <http://www.afosr.af.mil/ResearchAreas/special_pret.htm>.

⁴¹ Robotics Institute, “AFOSR PRET: Information Fusion for Command and Control: The Translation of Raw Data to Actionable Knowledge and Decision.” Available online at <http://www.ri.cmu.edu/projects/project_483_text.html>.

Many types of operational scenarios require coordination of teams of autonomous or semi-autonomous robots where members of the team are heterogeneous and provide different capabilities. Often, they must team to enhance overall performance or to complete the mission more rapidly. To compensate for the spatial and temporal vagaries of members of such a heterogeneous team, Sycara's group at CMU has developed a novel, mixed integer, linear programming (MILP) scheme that is independent of environment size and uses a continuous time model, unlike previous formulations. This new algorithm and formulation has been extensively tested in simulations. The continuous time MILP scheme also minimizes the effect of path planning complexity, which should contribute immensely to finding the optimal solution to task allocation among robotic team members.⁴²

The emerging science and engineering discoveries currently being supported by the AFOSR in the area of autonomous, decentralized control networks and the related area of information fusion for command, control, and decisionmaking are laying the groundwork for new, autonomous operator capabilities. The advances being spawned by discoveries in these areas will have immeasurable impact in meeting the challenges posed in Air Force FLTCs 1–5. Significant new capabilities to be generated by scientific discoveries allowing for greater utilization of autonomous, unmanned operators for both the military and homeland defense communities include, but are not limited to: surveillance and reconnaissance, search and rescue, tracking and targeting, long endurance operations, satellite maintenance, effects delivery, and critical operations in urban environments that we are incapable of doing today.

Identifying, Tagging and Tracking

One of the key capabilities that the military needs to win the Global War on Terror (GWOT) is the ability to quickly and accurately identify and then to tag and track adversaries and the critical materiel resources they use. This capability is clearly embodied in several of the Air Force FLTCs, particularly in FLTC 2, which deals with proactive surveillance and reconnaissance, and FLTC 3, which deals with difficult surface target engagement and defeat.

The present and future involvement of the United States in irregular warfare, with a major emphasis on counterinsurgency and stability operations, is really about people, not platforms, and thus must focus on the social context. Current basic research being supported by AFOSR in a new program focused on understanding the social and cultural dimensions of the behavior of adversaries will lead to new techniques to identify individuals and groups that pose potential threats to U.S. interests and how they might respond across a spectrum of actions, from humanitarian assistance to hostile engagement.

⁴² Koes, M., Nourbakhsh, I., and Sycara, K., "Heterogeneous Multirobot Coordination with Spatial and Temporal Constraints," *Proceedings of the Twentieth National Conference on Artificial Intelligence (AAAI)*, AAAI Press, June 2005, 1292-1297.

A second novel research program, focused on understanding the fundamentals of bioluminescence and how to manipulate bioluminescent molecules, holds high potential for developing new taggants that can be used to tag and track targets of interest. Some highlights of these exciting, new research efforts are discussed in this section.

Social-Cultural Modeling

In today's fast paced and ever changing military environment, it is critically important to correctly and accurately identify potential adversaries and not turn neutral parties into adversaries. Culture and society are significant factors in shaping adversarial attitudes, intentions, and behaviors. Thus, understanding the social-cultural environment and its influence on behavior is critical to deciding who are adversaries and what action should be taken to achieve the desired effects and expected outcomes from engagement with those adversaries. One way of understanding the social-cultural interactions and influence is to develop conceptual and instructive models of organizations and individual and group dynamics.

Ziggurat of Zealotry

A model developed by the Central Intelligence Agency (CIA) portrays a way of looking at the problem of making radicals out of peace-loving Muslims. This model referred to as the "Ziggurat of Zealotry," places Islamists in a Mesopotamian style pyramid, where each ascending level is a higher degree of radicalism. The model suggests that recruiters from one level recruit almost exclusively from the level below them. It further implies that radicalization is not inevitable. That is to say, radical Muslims are not destined to be violent terrorists. The model suggests that one can inhibit the move up the pyramid of radicalization by disrupting the movement of individuals and resources up the ziggurat.

Reference: Shainin, J., "The Ziggurat of Zealotry," *The New York Times*, December 10, 2006.

While conceptual models are useful, the predictive ability of such models is extremely limited. To develop models of social-cultural influences on behavior that could be used to predict adversarial behavior in individuals and groups, AFOSR began a new research program in 2004 focused on the creation of computational models of adversarial attitudes and behaviors. In 2005 and 2006, three new MURI programs were initiated to bring together social scientists, psychologists, political scientists, and public policy practitioners with computational scientists working in engineering, artificial intelligence, and cognitive sciences to begin tackling this problem from a number of novel, multifaceted approaches.

Dr. Whitman Richards, an expert in cognition and artificial intelligence at MIT, leads a multidisciplinary team whose objective is to bring together models of beliefs, attitudes, and sacred values and their consequent behaviors at the level of the individual, the group, and the governing body to show how the levels interact and influence one another. This

team, which includes members from the University of Michigan, Northwestern University, the University of Texas, and Harvard University, along with the MIT scientists, hopes to be able to forecast patterns of behavior when cultural forces clash. Studies of terrorist networks and the belief revisions underlying their dynamics is an important part of the research.⁴³

A second MURI is being led by Professor Alex Levis at George Mason University (GMU) in a partnership with Dr. Kathleen Carley at Carnegie Mellon University (CMU) under the title “Computational Modeling of Adversary Attitudes and Behaviors (CMAAB).” The main objective of this team is to explore, using computational modeling, the coupling of data and models for individual adversaries and organizations of adversaries. They expect to be able to relate an adversary’s organizational structure to behavior when both structure and behavior are influenced by cultural and social characteristics.⁴⁴ A recent scientific paper by the GMU group contributes a new computational technique that offers a standard way to analyze and describe very complex situations to help make decisions about actions that may be taken to achieve effects and avoid undesirable consequences on both the adversary and the population as a whole.⁴⁵

“Cognitive Architecture for Reasoning about Adversaries” is the name of the newest multidisciplinary team effort within the “Dynamic, Adaptive Techniques for Adversary Behavior Modeling” MURI category supported by AFOSR. This multi-university effort is lead by Drs. Dana Nau and V. S. Subrahmanian of the University of Maryland and includes team members from the University of Pennsylvania. The focus of the effort within the Laboratory for Computational Cultural Dynamics is to develop understanding and reasoning about cultures and to develop the computational models necessary to making good decisions applicable to war and counterterrorism operations, as well as to help reconstruct post-conflict and post-disaster societies. An initial focus of the work will be on tribes in the Pakistan-Afghanistan border region.⁴⁶ Although they have just begun, and much work remains to be done on estimating how adversaries will behave in the real world in a given scenario, the Maryland team has already developed the first version of an architecture for gathering data about different cultural groups, learning the opinions those groups have on various important topics, and developing models of behavior of those groups. The ability to refine those models through shared, multi-person learning experiences is a critical aspect of the architecture called a Cultural Adversarial Reasoning Architecture (CARA). CARA provides a paradigm to infer behavioral models of the

⁴³ MIT Computer Science and Artificial Intelligence Laboratory (CSAIL), “Belief Dynamics and Cultural Shifts.” Available online at <<http://publications.csail.mit.edu/abstracts/abstracts06/richards/richards.html>>.

⁴⁴ Communication with Dr. John Tangney, Program Manager, Air Force Office of Scientific Research, December 12, 2006.

⁴⁵ Wagenhals, L.W., and Levis, A.H., “Course of Action Analysis in a Cultural Landscape Using Influence Nets,” *Computational Intelligence for Security and Defense Applications*, IEEE, accepted November 7, 2006.

⁴⁶ University of Maryland Laboratory for Computational Cultural Dynamics (LCCD). Available online at <<http://www.umiacs.umd.edu/research/LCCD>>.

opponent and determine best what the opponent might do. Then one can reason about how to elicit the desired response from the adversary.⁴⁷

Bioluminescence

The main goal of AFOSR's Biomimetics, Biomaterials, and Biointerfacial program is to study, use, mimic, or alter how materials, processes and structures from nature accomplish a desired task, or to enable them to do a specific task to produce materials and systems for future Air Force technologies.⁴⁸ One of the new areas recently sponsored by AFOSR is research on bioluminescence.

First described by Anaximenes in 500 BC, bioluminescence is the emission of light produced by a chemical reaction within an organism. Predominantly a marine phenomenon, bioluminescence occurs at all depths in the ocean, but is most commonly observed on the ocean's surface, where it is recognizable by its blue-green color. In the terrestrial environment, some species of earthworms, fungi, and insects such as fireflies produce bioluminescence, which is believed to be used to attract prey and mates, evade predators, and communicate within species.

At least two chemicals are required for bioluminescence to occur in an organism, luciferin, which produces light, and luciferase, which catalyzes the oxidation of luciferin, resulting in light and an inactive chemical, oxyluciferin.⁴⁹ The major luciferin types that have been characterized are bacterial luciferin, dinoflagellates, vargula, coelenterazine, and firefly.⁵⁰

AFOSR has awarded a number of grants to conduct research on bioluminescence. Dr. Dimitri Deheyn, of the Scripps Institution of Oceanography at the University of California San Diego, is leading a team looking at optical, biochemical, and molecular characterization of new bioluminescence systems with the objective of characterizing compounds capable of producing light for possible application in biochemistry, biotechnology and engineering. Dr. Deheyn's research has looked at bioluminescence in the marine and terrestrial environment, conducting studies on characteristics of the marine polychaete, *Odontosyllis phosphorea*, and on a tropical terrestrial fungus.

To date, the project has screened more than 200 species of invertebrates from California, Panama, and Antarctica for light-producing capacity. Data from the screening suggest that the further away from the equator the less ability to produce light through fluorescence.⁵¹ The team is also conducting research on a tropical terrestrial fungus and

⁴⁷ Subrahmanian, V.S., Albanese, M., Martinez, M.V., Nau, D., Reforgiato, G.I., Sliva, A., Udrea, O., and Wilkenfeld, J., "CARA: A Cultural-Reasoning Architecture," *IEEE Intelligent Systems*, March/April 2007, 12-15.

⁴⁸ AFOSR, "Biomimetics, Biomaterials, and Biointerfacial Sciences." Available online at <http://www.afosr.af.mil/ResearchAreas/research_chem_biomimetics.htm>.

⁴⁹ Chemistry of Bioluminescence. Available online at <<http://www.lifesci.ucsb.edu/~biolum/chem/>>.

⁵⁰ Ibid.

⁵¹ Communication with Dr. Hugh De Long, Program Manager, Biomimetics, Biomaterials, and Biointerfacial Sciences, Air Force Office of Scientific Research, December 12, 2006.

has discovered that light production in the fungus is a continuous phenomenon that does not change between day and night, and that bioluminescence of the fungus increased immediately upon exposure to water.⁵²

A second AFOSR sponsored project, led by Dr. Bruce Branchini, of Connecticut College, is conducting “Characterization and Mutagenesis Studies to Develop Novel Bioluminescent Systems.”⁵³ The goals of the project are to: develop a novel bright flash and/or glow emitting sources of red (> 610 nm) and green (< 555 nm) light based on the firefly (*Photinus pyralis*) luciferase; characterize the biochemistry of the firefly luciferase-luciferin reaction; discover new bioluminescence enzymes; and characterize the structure and properties of the chromophores of *O. phosphorea*.⁵⁴ Dr. Branchini and his research team have developed novel methods for purifying the protein that catalyzes the light-emitting reaction and have also used synthetic organic techniques to prepare novel substrates for the firefly luciferin and substrates for a bioluminescent jellyfish.⁵⁵

Bioluminescence has wide ranging uses for both the scientific, commercial, and military communities. Bioluminescent materials are non-toxic and biodegradable, and can potentially be used in the future in diagnostic systems, lighting, detection of biohazardous materials in water, and in medical research. Possible applications of bioluminescent materials in breakthrough Air Force technologies and systems include biodegradable landing zone markers, anti-tamper systems, perimeter security systems, friend versus foe marking systems, and tactical and logistical illumination. Bioluminescence materials will also play a significant role in tracking mission essential materials, such as weapons, energy supplies, and equipment. They can be stationary, but in today’s world they are often mobile. On the battlefield, being able to tag and then track weapons and supplies will greatly benefit the logistics of a mission.

Getting There Faster

Current and future Air Force research on hypersonics can make a substantial contribution to FLTC 7, “On-Demand Theater Force Projection, Anywhere,” which is aimed at pursuing revolutionary improvements in the efficiency and responsiveness of transporting air, space, and cyber capabilities to the operational and tactical warfighter. Various programs at AFOSR conduct research applicable to FLTC 7, including the Boundary Layers and Hypersonics Program, which is focused on providing the fundamental fluid and physics knowledge for future aerospace systems. Research supported by this program enables methods for flow prediction and optimization that, in the short term, will reduce

⁵² Deheyn, D.D., and Latz, M.I., “Bioluminescence characteristics of a tropical terrestrial fungus (Basidiomycetes),” submitted to *Luminescence: The Journal of Biological and Chemical Luminescence*.

⁵³ Connecticut College, “Bioluminescence Research Group at Connecticut College: Research Funding,” January 14, 2005. Available online at <<http://www.conncoll.edu/academics/departments/chemistry/BRG/funding.html>>.

⁵⁴ Communication with Dr. Hugh De Long, Program Manager, Biomimetics, Biomaterials, and Biointerfacial Sciences, Air Force Office of Scientific Research, January 16, 2007.

⁵⁵ Connecticut College, “Air Force grant to CC professor highlights link between academic research and the fight against terrorism,” April 14, 2004. Available online at <<http://aspen.conncoll.edu/camelweb/index.cfm?fuseaction=ccnews&id=1208>>.

the weight and cost of future systems, and, in the long term, will enable completely new, revolutionary vehicle designs for the Air Force.⁵⁶ This program looks at two key issues that have a direct impact on hypersonic flight: aerodynamics and aerothermal management.

Fluid mechanics research, specifically on the transition of boundary layers from laminar flow to turbulent flow, is key in the development and optimization of future high-performance air vehicles. The boundary layer is the thin region near the surface of a vehicle where viscous effects are significant. Virtually every Air Force atmospheric vehicle is impacted by boundary layer transition. In the transition of the boundary layer from a laminar to turbulent state, smooth flow is replaced by unsteady, random fluctuations of fluid eddies of varying scale. As a result, mixing within the flow field is greatly enhanced, and both skin friction drag and surface heat transfer rates increase dramatically. The turbulent boundary layer is also more robust than the previous laminar state and, thus, more resistant to separation, in which the boundary layer separates from the vehicle surface and dramatically alters the effective aerodynamic shape. Hence, the impact of boundary layer, laminar-turbulent transition on an Air Force system can both hinder performance through increased drag and heat transfer and enhance performance through resistance to performance-limiting separation.⁵⁷ Research in the Boundary Layers and Hypersonics Program is ongoing in addressing the issue of the transition from laminar to turbulent flow. Ultimately, research efforts in the program are aimed at being able to control both flows, turning them “on and off” as desired. This research could revolutionize hypersonics by allowing the Air Force to control the flow over and within atmospheric vehicles and increase mach speed. Research on laminar and turbulent flows, however, also incorporates aerothermal management.

Extreme surface heating rates make the hypersonic regime the most challenging flight system operational environment. Very little is known of the coupled aerothermodynamic, chemical, and material interactions at the vehicle surface. The problem is exacerbated by a general inability to exactly reproduce the hypersonic environment in ground test facilities. In an effort to overcome these difficulties, the Boundary Layers and Hypersonics Program and the Ceramic and Nonmetallic Materials Program at AFOSR have developed a joint program to conduct research on aerothermodynamic, chemical, and material interactions on the skin and the propulsion system of hypersonic vehicles.

In hypersonic flight, materials experience extreme thermal and chemical environments that can diminish the structural integrity of the vehicle. One materials challenge facing the structure is the skin of the vehicle, which must withstand an operating environment that has temperatures in excess of 1500 degrees centigrade. Once a material is heated to these high temperatures, thermal stresses can cause micro-cracks in the thermal protection system of the skin, leading to catastrophic failure of the structural integrity of the skin. Another challenge involves the engine of the vehicle, where sustained

⁵⁶ Schmisser, J., Air Force Office of Scientific Research, “Boundary Layer and Hypersonics.” Available online at <http://www.afosr.af.mil/ResearchAreas/research_aero_boundary.htm>.

⁵⁷ Communication with Dr. John Schmisser, Program Manager, Boundary Layers and Hypersonics, Air Force Office of Scientific Research, January 31, 2007.

temperatures above 2500 degrees centigrade are experienced. The propulsion system of the vehicle will require materials that can withstand both extreme chemical and thermal environments over prolonged periods of use.

Of particular interest to the joint AFOSR program are research projects that focus on the rapid discovery of new/novel ceramic materials that are both lightweight and high-temperature-tolerant ($>1500^{\circ}\text{C}$), such as borides, carbides, and nitrides of early transition materials. To facilitate their use, these materials' resistance to oxidation must be improved, and lower cost processing routes to complex shaped components must be discovered.⁵⁸ These materials could be used to control chemical reactions in the vehicle



Concept for a Future
Hypersonic Aircraft

boundary layer, reduce skin friction drag and heating, and control plasma generation. Key basic research on these materials includes analysis of borides and carbides, which have melting temperatures above 3000 degrees centigrade, retain their strength at temperatures above 1200 degrees centigrade, exhibit thermal shock resistance, and can be modified with additives to promote oxidation resistance.⁵⁹ The limiting factor for these materials is their lack of

an affordable, reproducible manufacturing process and the limited number of borides and carbides that have been explored.⁶⁰ Further research on the development of new materials testing methodologies and the discovery of new compounds is extremely important.

In the long term, this research will provide materials and technologies that will enable revolutionary improvements in the design of hypersonic vehicles, impacting both the skin of the vehicles and the propulsion systems. This research will not only increase the survivability and reusability of Air Force vehicles, but will also allow for the addition of different types of payloads to the vehicles.

Assured Cyber Engagement

The new Air Force mission domain of cyberspace is defined succinctly by the Department of Defense as “the notional environment in which digitized information is communicated over computer networks.”⁶¹ Research in cyberspace covers a wide expanse of potential topics, ranging from sensors that collect the initial information through networks that transmit information to decisionmakers who must utilize information to make critical and often time sensitive decisions. A recent study conducted by the National Research Council of the National Academies titled “Basic Research in

⁵⁸ Fuller, J., Air Force Office of Scientific Research, “Ceramic and Nonmetallic Materials.” Available online at <http://www.afosr.af.mil/ResearchAreas/research_aero_ceramic.htm>.

⁵⁹ Fahrenheitz, W.G., and Hilmas, G.E., “NSF-AFOSR Joint Workshop on Future Ultra-High Temperature Materials,” April 12, 2004. Available online at <http://web.umn.edu/~uhtm/UHTM_wkshp_draft_rpt.pdf>.

⁶⁰ Ibid.

⁶¹ Department of Defense Dictionary of Military and Associated Terms (Joint Publication 1-02), April 12, 2001 (as Amended through 9 November 2006). Available online at <http://www.dtic.mil/doctrine/jel/new_pubs/jp1-02.pdf>.

Information Science and Technology for Air Force Needs” stated “the main challenge of Air Force communications is to provide assured connectivity between networks.” The report from that study further stated “research in security is needed in support of the goal of measurable, available, secure, trustworthy, and sustainable network-enabled systems.”⁶²

Partially in response to that study, AFOSR has recently increased emphasis in research that contributes to protecting our information systems and assuring that the information upon which decisions must be made is uncorrupted, free of deception and that networks are secure. This area of research, collectively referred to as Information Assurance (IA), will provide results directly applicable to Air Force FLTCs 5 and 6 dealing with challenges in Assured Operations in High Threat Environments and Offensive Cyber engagement, respectively. The discussion in this section will focus on research in IA by highlighting current AFOSR basic research dealing with deception detection, assured information sharing, and a new Cybercraft concept for protecting information systems.

One of the issues in assuring a trustworthy information system is keeping deceptive messages out of the information, or at the very least being able to detect that deception has occurred. A related issue is being able to find the origin of that deception once it is detected using steganographic or digital forensics methods. Steganography is the art of hiding the presence of communication by embedding messages into innocuous cover documents, such as digital documents, images, video and audio files. Detection of steganography and its extraction is the field of steganalysis.⁶³ Digital images make up a critical part of the information stream needed for operators to make strategic and tactical decisions.

AFOSR is supporting Professor Jessica Fridrich at Binghamton University, who is investigating advanced digital forensics and steganalysis methods that will reveal tampering with images and prevent digital forgeries. Fridrich’s laboratory has developed a new method for detection of digitally manipulated images based on sensor pattern noise that each camera involuntarily inserts into each image it takes. Because the pattern noise is a unique stochastic fingerprint of digital imaging sensors, forged areas can be identified by verifying the consistency of their noise residual with the pattern noise of the particular sensor element. Research results indicate that it is possible to reliably identify forged regions even in images that were JPEG compressed with quality factors as low as 70.⁶⁴ Development of steganalysis techniques and cyber forensic methods such as this and others under development will help to assure that information in cyberspace operations can be trusted by allowing the removal of tampered with information.

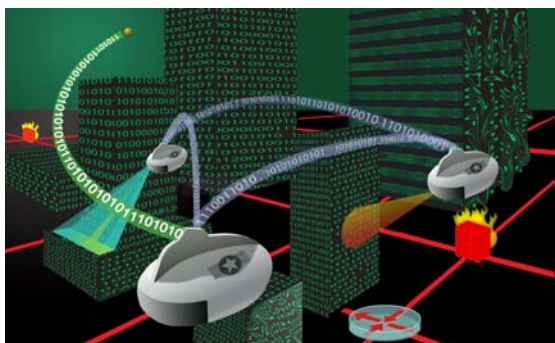
⁶² National Academies, *Basic Research in Information Science and Technology for Air Force Needs* (Washington, DC: The National Academies Press, 2006).

⁶³ Fridrich, J., and Goljan, M., “Practical Steganalysis of Digital Images – State of the Art,” *SPIE Electronic Imaging, Photonics West*, January 2002.

⁶⁴ Lukas, J., Fridrich, J., and Goljan, M., “Detecting Digital Image Forgeries Using Sensor Pattern Noise,” *SPIE Electronic Imaging, Photonics West*, January 2006.

A critical issue in information or cyberspace operations where a large number of diverse coalition members are involved is dealing with information sharing across the various infospheres of all the different coalition partners. Each partner brings its own security policies regarding information sharing, and the issue of trust levels (trustworthy, semi-trustworthy, and untrustworthy) among the various partners is an issue of major concern. With support from AFOSR, Professor Bhavani Thuraisingham, who directs the CyberSecurity Research Center at the University of Texas at Dallas, is investigating access control and usage control policies for secure data sharing across trust levels. Although this research just began in 2006, an experimental system for determining information loss due to security policy enforcement among trusted partners in a coalition has already been developed. In addition, new strategies involving the application of game theory and novel data mining techniques for use in extracting information and for conducting defensive operations with less trustworthy groups have been developed and are being tested using simulations and other experimental paradigms.⁶⁵ The techniques being developed will provide new capabilities for enhanced interoperability across the infospheres of various coalition partners. Coalition operations will be the preferred strategy for the foreseeable future. Effective coalitions are essential to winning the Global War on Terror. Assured information sharing is essential to creating effective coalitions.

A novel concept for guaranteeing the security and assurance of cyber systems referred to as a “Cybercraft” has been proposed by Dr. Paul Phister and his associates at the Air Force Research Laboratory’s Information Directorate (AFRL/IF).⁶⁶ The networks and other components that comprise the Net-Centric Enterprise Services (NCES) that form the backbone of Air Force and DOD cyberspace operations are complex and dynamic, making it very difficult to secure. The Cybercraft concept embodies an agent that can be launched from a security or network management station.



Cybercraft Would Operate Autonomously to Defend Military Information Systems

The Cybercraft would have the ability to accurately map networks, search network nodes, identify and report anomalous and malicious behavior, and, ideally, take corrective action. Obviously, to be effective, the Cybercraft system must be trusted by commanders and those who rely on it to act autonomously and defend military information systems. A new basic research effort under AFOSR support is being led by Dr. Kamal Jabbour at AFRL/IF.

⁶⁵ Department of Computer Science, University of Texas at Dallas, “Assured Information Sharing,” Data and Applications Security Research Group, 2007. Available online at <http://www.utdallas.edu/~bxt043000/2007.htm>.

⁶⁶ Phister, Jr., P.W., Fayette, D., and Krzysiak, E., “CyberCraft: Concept Linking NCW Principles with the Cyber Domain in an Urban Operational Environment,” unpublished paper. Available online at <http://www.au.af.mil/au/awc/awcgate/afri/cybercraft.pdf>.

The research effort, which just began this year, will focus on an investigation of sensors for network anomaly detection, communication architectures and protocols, scalability issues for determining fleet sizes, and techniques for assuring reliability. While prototype Cybercraft are many years away, the basic research needed to underpin the development of this exciting capability for protecting and assuring the security of future Air Force cyber operations has begun.

Summary and Conclusion

This paper has discussed four critical areas where the Air Force needs new capabilities to carry out future missions in air, space, and cyberspace: 1) autonomous, unmanned vehicles; 2) identifying, tagging, and tracking entities; 3) getting to the area of operations faster; and 4) assured cyber engagement. It highlighted a few of the exciting basic research efforts being supported by the AFOSR that hold great promise of generating the new understanding needed to meet the challenges posed by those capability needs and others articulated in the Air Force FLTCs, as well as those identified in the 2006 QDR. In concluding, two thoughts require emphasis: the importance of basic research and the need for policy to inform science, technology, and new capabilities and, equally important, the reverse—for science, technology and the potential new capabilities to inform policy.

Basic Research: Origin of New Capabilities

Basic research is the key investment for assuring the future ability of the Air Force and the Department of Defense to meet the unanticipated mission needs of an unknowable future. Fundamental research provides the understanding of natural phenomena that is critical to creating new technical options, as well as new processes and procedures, required to be an agile force in a world in flux. This point is best stated in a National Academies report assessing the Department of Defense's basic research program: "... resources committed to basic research create and deliver a portfolio of future valuable returns. It is useful to think of these investments as resulting in options which, if exercised, will lead to solutions for future military challenges as they emerge. The outputs of basic research are not the options themselves, but rather the raw materials used to construct the options ..."⁶⁷ In essence, basic research is the wellspring of our national security.

Interfaces: Technology/Capability/Policy

One important issue that surfaced during the research for this paper is the important interplay of science, technology, and new capabilities with policy. There is a need for policy to inform the direction of science and technology programs as they underpin the development of new capabilities. Perhaps more important is the reverse—the need for science, technology, and the potential new capabilities to inform policy development. For example, in the development of technologies for new autonomous vehicles, lines of research could be better informed if the bodies that establish operational doctrine and policy for use of such vehicles could clearly answer questions such as: How, when and where will autonomous operators be used? How autonomous should they be? What legal and policy imperatives will impact the use of autonomous, unmanned operators? Answers to such questions could fruitfully influence the direction and emphasis of the research program to focus, for example, on achieving a specific degree of semi-autonomous

⁶⁷ National Research Council of the National Academies, *Assessment of Department of Defense Basic Research* (Washington, DC: The National Academies Press, 2005), 15.

operation and control vice totally autonomous operation. Equally important should be the ability of the scientist and engineer to influence the establishment of policy or doctrine if they can demonstrate the real likelihood of trusted capabilities related to autonomous operators that might then allow a greater degree of autonomy in unmanned vehicles and robotic platforms. Similarly, if we understand in detail the mechanisms that would be used by adversaries to inhibit or corrupt our cyber operations to the point that we can assure the security and validity of our Net-Centric Enterprise Services, then it is at least implied that our understanding would allow us the capability to launch offensive cyber operations. What, then, are the implications of such new capabilities for policy and doctrine for cyber warfare?

While other questions and examples could be given, we believe these make the point. Early on in the process of spawning new technical capabilities, basic research scientists and engineers should be engaged with those professionals involved in developing policy and doctrine for operations to assure a better understanding of all the potential uses of the new technologies and capabilities to better inform the shaping of new policies.